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VERY HIGH REPETITION RATE POWER SUPPLY SYSTEM AND METHOD

TO WHOM IT MAY CONCERN:

BE IT KNOWN THAT George L. Bees of 12 Woodstock Drive, Framingham, Middlesex County, Massachusetts, 01701, invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates generally to power supply systems, and more particularly to power supply systems for high repetition rate pulse discharge driven systems.

(2) Description of the Prior Art

A large ampere current pulse that is a requirement of pulse discharge driven systems, is often realized through a capacitor that is charged to a certain voltage and discharged at a specified time to deliver the energy required of the pulse discharge driven system. Examples of pulse discharge driven systems include Doppler radar and lasers. In these systems, it is necessary to deliver the energy from the capacitor to the system in a precise manner, wherein the precision relates to the timing of energy delivered, and the amount of energy delivered. For instance, in a Doppler radar system, it is necessary to deliver the same energy each pulse repetition interval to allow the return signals to be properly processed, as fluctuations in the delivered energy may cause variability in the transmitted pulses that are then misinterpreted by the receiver. Similarly, a laser system requires the same precision in timing and energy

for proper laser operation, as there is a nonlinear relationship between the energy delivered and the laser performance.

Prior art power supply systems utilize peaking capacitors in magnetic pulse compression circuits to provide a repetitive, high voltage, high energy charge to a peaking capacitor in a short duration. In such systems, multistage LC networks typically convert long, relatively low voltage pulses into the desired short, high voltage pulses. Other prior art systems include pulse power supply systems that supply excimer lasers with high voltage, short pulses. The majority of the prior art systems, however, operate in the 1000 Hz range. One prior art system operating at higher frequencies does not allow asynchronous operation, as the power supply system operation is coordinated precisely with the pulse discharge driven system. In that prior art system, the timing between the pulse discharge driven system and the charging capacitor reaching a specified voltage, must be synchronized precisely, as the problem of maintaining a specified voltage across a capacitor is well-known.

There is not currently an asynchronous power supply system for pulse discharge driven systems, wherein the power supply system may operate at higher repetition frequencies and not require synchronous coordination with the pulse discharge system.

What is needed is an efficient power supply system to accurately operate at higher pulse rates, wherein the power

supply system may operate asynchronously with respect to the pulse discharge driven system.

SUMMARY OF THE INVENTION

It is an aspect of the invention to provide a power supply system that supplies electrical pulses to a pulse discharge driven system. In one aspect of the invention, the power supply system includes a pulse generating circuit with a charging inductor and a charging capacitor, wherein the charging capacitor drives the pulse discharge driven system. It is another aspect of the invention to select the charging inductor to achieve a time constant that is coordinated with the pulse rate of the pulse discharge driven system.

In one embodiment, the pulse generating circuit further includes a "keep up" high-voltage power supply, three solid-state switches, and a diode. The voltage across the capacitor is initially charged through the main power supply, wherein the time to charge the capacitor is determined in part by the charging inductor value. The capacitor voltage is monitored and compared to a predetermined "control" voltage that is less than a "driving" capacitor voltage that satisfies the requirements of the pulse charge driven system. Upon the capacitor voltage attaining the control voltage, a control module commands a solid-state switch to disconnect the main power supply from the circuit, thereby resulting in a sourceless (R)LC circuit that

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allows the capacitor to continue charging at a more controlled rate through the inductor discharge. Once the capacitor charges to the driving voltage, the control module commands two solid-state switches to separate the inductor from the capacitor, and similarly, the control module commands the keep-up supply to monitor and maintain the capacitor charge. If the capacitor discharges before the pulse discharge system utilizes the capacitor charge, the keep-up power supply replenishes the capacitor charge to the driving voltage.

It is another aspect of the invention that when the capacitor is discharged by the pulse discharge system, the control module returns the pulse generating circuit to its original state, incorporating the main power supply and inductor by returning the solid-state switches to their original states.

It is another aspect of the invention to supply power to a pulse discharge driven system, wherein the pulse discharge driven system is a laser.

Other objects and advantages of the invention will become obvious hereinafter in the specification and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the invention and many of the attendant advantages thereto will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in conjunction with the

accompanying drawings, wherein like reference numerals refer to like parts and wherein:

FIG. 1 displays a power supply system that incorporates the principles of the invention;

FIG. 2 displays the power supply system circuit of FIG. 1 while the power supply system is charging a capacitor from the main power supply;

FIG. 3 presents the power supply system circuit of FIG. 1 wherein the capacitor is charging from an inductor;

FIGs. 4a and 4b present the power supply system circuits derived from the power supply system of FIG. 1, wherein the keep-up supply is maintaining the capacitor charge; and,

FIG. 5 illustrates the capacitor charging cycle throughout the power supply system circuits of FIGs. 2-4B.

DESCRIPTION OF ILLUSTRATED EMBODIMENTS

To provide an overall understanding of the invention, certain illustrative embodiments will now be described; however, it will be understood by one of ordinary skill in the art that the systems described herein can be adapted and modified to provide systems for other suitable applications and that other additions and modifications can be made to the invention without departing from the scope hereof.

Referring now to FIG. 1, there is shown a power supply system **10** that incorporates the principles of the invention. As illustrated in FIG. 1, the power supply system **10** charges a capacitor **12** that is coupled through a switch **14** to a pulse discharge driven system **16**. Those skilled in the art will recognize that the capacitor **12** is merely illustrative and may be represented by any other well known component with capacitive properties. Similarly, examples of pulse discharge driven systems include lasers and Doppler radars, for example, although this invention is not limited to a specific pulse discharge driven system. For the purposes of this discussion, the pulse discharge driven system **16** will be referred to as a laser. The switch labeled S4 **14** and otherwise referred to herein as S4, may be any switching device or circuitry that applies the capacitor voltage to the laser **16**, and may include solid state switches, for example. In the FIG. 1 illustration, an S4 control system may control S4 **14**, wherein such control system is not depicted in

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FIG. 1. The S4 control system may operate S4 **14** according to laser pulsing requirements. For example, if the laser operates at a frequency of 2000 Hz, the S4 control system may cause S4 **14** to close every 500 microseconds for a predetermined length of time.

The power supply system **10** as illustrated charges the capacitor **12** to ensure that the capacitor voltage is the value required to drive the laser **16**, hereinafter referred to as the driving voltage. The capacitor value is therefore dictated by the laser **16** specifications. Because pulse driven systems such as lasers have operational characteristics that are nonlinear with respect to the driving voltage, it is a necessary requirement that the driving voltage be accurately determined and delivered. As FIG. 1 illustrates, the driving voltage for the laser **16** is provided by the capacitor **12**, and the difficulties of maintaining a constant and precise charge across a capacitor are well known in the art. The FIG. 1 power supply system **10**, however, discloses a system wherein resonant circuitry is incorporated to maintain a specified driving voltage across the capacitor **12**.

The various elements of the power supply system **10** are illustrated in FIG. 1, and are described relative to FIG. 1 briefly, with the detailed operation and interconnections to be further detailed and understood by the descriptions of FIGs. 2, 3, and 4. As FIG. 1 indicates, the power supply system **10**

includes a main power supply **18**. In an embodiment, the main power supply **18** is a 20 KW phase shifted zero voltage switch pulse width modulated (PWM) converter, operating at approximately 40 KHz, that converts three-phase line power to 1200 VDC, although such power supply specifications are merely illustrative and the invention herein is not limited to any specific main power supply. The illustrated system **10** also includes three switches labeled S1 **20**, S2 **22**, and S3 **24**, all of which may be any switching device, but in an embodiment, all of which are solid state switches. The invention does not require that the switches be of same or similar type to each other.

The illustrated charging inductor **26** is selected to provide a time constant that allows a capacitor charge time that satisfies, i.e., is less than, the pulse rate of the laser **16**. For the illustrated system, for example, the charge time is approximately equal to $\pi * \sqrt{L*C}$. Two resistors, R1 **28** and R2 **30**, are connected in parallel with the capacitor **12** in a commonly known voltage divider configuration. A keep-up power supply **32** is also connected in parallel with the capacitor **12**, and in an embodiment, the keep-up power supply **32** is a high voltage power supply, although the invention is not limited by the keep-up power supply **32** specifications, and any similarly functioning element as described herein, may therefore be substituted without departing from the invention. The power supply system **10** also includes a control module **34** that operates S1 **20**, S2 **22**, S3 **24**,

and controls the operation of the keep-up power supply **32**, and the main power supply **18**. The illustrated control module **34** is not microprocessor based, however those skilled in the will recognize that the control processor may be a microprocessor based device, including for example, a personal computer (PC), SUN workstation, laptop or handheld computer including personal digital assistant (PDA), connected through a network or in a stand-alone capacity, and functioning as described herein, without departing from the scope of the invention. As FIG. 1 indicates, the control module ~~**24**~~ 34 and the keep-up power supply **32** measure the voltage drop across R1 **28**. The remaining element of the power supply system **10** is a diode **36**.

Referring now to FIG. 2, there is illustrated a simplified power supply system circuit **40** that is representative of the FIG. 1 power supply system **10** wherein switches S1 **20** and S2 **22** are closed, and switch S3 **24** is open. Recall from FIG. 1 that the S1 **20**, S2 **22**, and S3 **24** switch operation is controlled by the control module **34**. The FIG. 2 illustration is representative of the initial charge configuration, and shall be referred to herein accordingly.

From FIG. 2, one with ordinary skill in the art will recognize that the main supply **18** charges the capacitor **12** and inductor **26**. The control module **34** immediately and continually monitors the voltage across R1 **28** to maintain an accurate measurement of the voltage across the charging capacitor **12**.

Once the control module **34** determines that the capacitor **12** is charged to a predetermined percentage of the specified driving voltage, the control module **34** commands S1 **20** to open, thereby disconnecting the main power supply **18** from the remainder of the power supply system **10**. The predetermined percentage may be a function of the driving voltage, the keep-up supply **32** characteristics, and the laser (pulse discharge driven system) **16** characteristics.

Referring now to FIG. 3, there is shown the simplified circuit of FIG. 1 wherein S1 **20** is open, S2 **22** is closed, and S3 is open. In an embodiment, this switch configuration, represented by the FIG. 3 circuit, is commanded by the control module **34** when the control module **34** measures that the capacitor **12** is charged to 95% of the driving voltage. As FIG. 3 indicates, the main power supply of FIGs. 1 and 2 is no longer connected to the circuit power supply system segment that includes the capacitor **12**. One with ordinary skill in the art will recognize that the sourceless circuit of FIG. 3 will cause the inductor **26** to discharge with an exponential decay, with current flowing through the diode **36**, and allowing the capacitor **12** to continue charging at a slower rate than the charge rate provided by the main power supply **18** in FIG. 2. The control module **34** continues to monitor the capacitor **12** through R1 **28**, and when the control module senses that the capacitor **12** has charged to 100% of the specified driving voltage, the control

system **34** commands S2 **22** to open, and S3 **24** to close. Additionally, the control module **34** activates the keep-up supply **32** to monitor and maintain the capacitor **12** charge.

FIGs. 4A and 4B represent the simplified circuit diagram of FIG. 1 wherein switch S1 **20** is open, S2 **22** is open, and S3 **24** is closed. As FIGs. 4A and 4B illustrate, the FIG. 1 power supply system **10** simplifies into two individual circuits for the given switch configuration. The circuit illustrated by FIG. 4A includes the main power supply **18**, the inductor **26**, and the diode **36**. Any energy remaining in the inductor **26** will be transferred to the main power supply **18**.

Alternately, the circuit illustrated in FIG. 4B includes the series combination of R1 **28** and R2 **30**, connected in parallel with the capacitor **12**, and similarly in parallel to the activated keep-up supply **32**. Those skilled in the art will recognize that if the capacitor **12** is not discharged by the laser **16** of FIG. 1 nearly immediately after the switch configuration represented by FIGs. 4A and 4B is achieved, the voltage across the FIG. 4B capacitor **12** will exponentially decay through R1 **28** and R2 **30**, and other system losses; therefore, the activated keep-up supply **32** monitors the loss through R1 **28** and compensates for the loss by recharging the capacitor **12**. In an embodiment, the illustrated keep-up supply **32** activates whenever the keep-up supply **32** determines the capacitor discharge loss exceeds one volt. The keep-up supply **32** continues to replenish the capacitor

12 to maintain the capacitor voltage at the desired driving voltage. This replenishing cycle performed by the keep-up supply **32** may continue indefinitely. In this configuration, the control module **34** also continues to monitor the voltage across the capacitor **12** by measuring the voltage drop across R1 **28**.

Those skilled in the art will recognize that the keep-up supply **32** monitoring and maintenance functions may be performed in many ways while remaining within the scope of the invention. For example, the keep-up supply **32** may receive and store the driving voltage, and compare the measured voltages to the stored driving voltage to determine when the capacitor **12** requires recharging. The keep-up supply **32** may measure the voltage across R1 **28** using well-known sample-and-hold technology, using either digital or analog circuitry, but the invention is not limited to such technique. Alternately, the control module **34** may provide the driving voltage to the keep-up supply **32**, or the keep-up supply driving voltage reference may be established as that voltage first measured by the keep-up supply **32** after the control module **34** activates the keep-up supply **32**.

Those skilled in the art will also recognize that the control module **34** may measure the capacitor voltage using many different well-known techniques, some of which are referred to in the discussion of the keep-up supply **32**, without departing from the scope of the invention. Because the illustrated control module **34** continuously monitors the voltage across the capacitor

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12, the control module **34** measures the significant capacitor voltage drop that occurs when, in the present example, the capacitor **12** is discharged by the illustrated laser **16** of FIG. 1.

The illustrated laser **16** of FIG. 1 presents an output load with extremely small impedance; therefore, when switch S4 **14** closes, the capacitor voltage is discharged to the laser **16**, but the load mismatch between the capacitor **12** and the laser **16** causes a reversal of current, and hence a reversal in the sign of the voltage at the capacitor **12**. Referring now to FIG. 5, there is shown the voltage across the capacitor **12** as a function of time **50**. As FIG. 5 indicates, the capacitor voltage is at the driving voltage **52** when S4 is closed **54**, whereupon within, for example, approximately five to ten microseconds in some applications, the capacitor **12** discharges, wherein the capacitor voltage drops from the driving voltage **52**, to a negative voltage **56**. Those skilled in the art will recognize that this negative voltage represents energy that may be expressed by the well known expression of $\frac{1}{2}CV^2$, where C is the capacitor **12** value, and V is the voltage across the capacitor.

Upon the control module **34** sensing the significant and nearly instantaneous capacitor voltage drop that occurs when S4 **14** is closed, the control module **34** returns the power supply system **10** to the initial charge configuration of FIG. 2, wherein S1 **20** is closed, S2 **22** is closed, and S3 **24** is open. Additionally, the control module **34** deactivates the keep-up

supply **32**. The power supply system **10** is therefore returned to the initial charge configuration of FIG. 2. In this configuration, however, the inductor **26** is connected to the main power supply **18** on one end, and the capacitor **12** with negative voltage at the other end. This difference in voltage, in combination with the diode **36** preventing current flow away from the inductor **26**, causes a large current surge through the inductor that transfers the energy in the capacitor **12** to the inductor **26** and facilitates a more responsive charge of the inductor and capacitor to meet the laser **16** requirements. This inherent recovery of capacitor **12** energy due to the capacitor voltage reversal facilitates a power supply system **10** that is compatible with higher repetition rate laser.

In alternate embodiments, the control module **34** may sense the discharge by the pulse discharge driven system **16** by receiving a signal from the pulse discharge driven system **16**, for example. Those skilled in the art will recognize that other methods of sensing the capacitor discharge may be incorporated without departing from the invention.

In another embodiment, the control module **34** may control the main power supply **18** for shut-down in the case of system failure.

This series of charging the capacitor **12**, in this example, to 95% of the driving voltage, as shown by FIG. 2, thereafter removing the main power supply **18** to allow the inductor **26** to continue charging the capacitor **12** to 100% of the driving

voltage, as illustrated and demonstrated by FIG. 3, and activating the keep-up supply **32** to maintain the capacitor charge as shown by FIG. 4B, continuously repeats with the required frequency and duration specified by the pulse discharge driven system **16**, wherein the cyclic capacitor voltage may be illustrated by FIG. 5. As shown by FIG. 5, although the illustrated power supply system **10** components are selected to satisfy a pulsing interval **58** of the laser **16**, it is not necessary that the power supply system **10** be synchronized precisely with the laser pulsing interval **58**. For example, prior art power supply systems that cannot indefinitely maintain the charge across the driving capacitor **12**, are coordinated precisely with the end of each pulsing interval **58** to ensure the fully charged capacitor condition occurs synchronously with the laser discharge.

One of several advantages of the present invention over the prior art is that the power supply system **10** may charge and thereafter maintain a charge across the capacitor **12** to drive the pulse discharge driven system **16**, wherein the capacitor charging and maintenance thereof is not required to be synchronized with the discharge by the pulse discharge driven system **16**.

What has thus been described is a system and method for a power supply system that charges a capacitor, wherein the capacitor charge drives a pulse discharge driven system. The power supply system utilizes a main power supply and a resonant

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inductor and capacitor configuration to charge the capacitor to a specified, large percentage of a driving voltage that is required by the pulse system. A control module monitors the capacitor charge and disconnects the main power supply when the capacitor charge is within the specified percentage. The main power supply disconnect causes the inductor to discharge and similarly charge the capacitor in a more controlled manner. Once the control module measures the capacitor voltage at the full driving voltage, the control module commands a switch to separate the inductor from the capacitor. The control module similarly activates a small high voltage power supply that monitors the capacitor and replenishes any natural capacitor discharge that may occur in the time between the full capacitor charge and the capacitor discharge by the pulse discharge driven system. Once the pulse discharge driven system discharges the capacitor, the control module returns the power supply system to its initial state, wherein the main power supply and residual energy in the capacitor cooperate to efficiently charge the inductor and capacitor. The charging cycle continues repeatedly as a function of the pulse discharge driven system requirements.

Although the present invention has been described relative to a specific embodiment thereof, it is not so limited. Obviously many modifications and variations of the present invention may become apparent in light of the above teachings. For example, the system presented herein represented a laser, but

other pulse discharge driven systems may be substituted. Although the example charged the capacitor to 95% of the driving voltage before separating and deactivating the main power supply, such criteria is merely for illustrative purposes and other values may be selected. The switches in an embodiment are solid state devices, however any other switching mechanism may be used. Similarly, all switches are not required to utilize the same technology. The main power supply represented may be any power supply supplying any waveform or signal sufficient to charge the inductor and capacitor to the desired values. Similarly, the keep-up supply may be substituted by any device or mechanism that may perform the functions described herein and attributed to the keep-up supply in measuring and maintaining the capacitor voltage. The control module includes any device capable of monitoring and controlling the switches and power supplies as described herein. Similarly, functions such as those described for the keep-up supply and control module, for example, may be combined into a single device without departing from the scope of the invention. The control module may sense that the capacitor was discharged by the pulse discharge driven system by measuring the voltage, or alternately, by monitoring the switch to the pulse discharge driven system, or obtaining a signal from a pulse discharge driven system control module, indicating that the capacitor was discharged. The voltage divider configuration may be eliminated and substituted with another scheme.

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Many additional changes in the details, materials, steps and arrangement of parts, herein described and illustrated to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention. Accordingly, it will be understood that the invention is not to be limited to the embodiments disclosed herein, may be practiced otherwise than specifically described, and is to be understood from the following claims, that are to be interpreted as broadly as allowed under the law.